History of Monopulse Radar in the US

David K. Barton

An IEEE AESS Historical Publication

Discourse

"From letters one makes syllables,
From syllables, words, and
From words discourse.
Do your duty by them." **

Discourse is *"the formal and orderly expression of thought on a selected subject."*

Systems encourages discourse in many forms: papers, contributions, tutorials, reports, and correspondence to name a few. If the subject aligns with society interests, or the contributors (and editors) feel that an as-yet-uncovered subject is worthy of discourse, we gladly welcome it.

Discourse publication by ***Systems*** will be handled thusly:

1) One item per issue;
2) There may be an *Introduction* by a guest editor if there is more than one section of the subject;
3) If multiple sections, all will be cross-referenced;
4) Discourse will be an "extra" in an issue -- it will not replace regular features; and
5) Comments on discourse items will appear as correspondence in succeeding issues.

In exceptional cases, with a suitable subject, it will be handled as a *Part Two* of a regular issue (as we do with *Tutorials*). For a series, we will include one item per issue, and not necessarily in consecutive issues. Discourse items and any comments thereupon will be cross-referenced and included in our *Annual Index.*

– Teresa Pace
Editor-in-Chief

** *From **Champ Fleury** (1529) by Geofroy Tory*
Translation by George B. Ives

History of Monopulse Radar in the US

David K. Barton

ABSTRACT

The history of development of monopulse radar in the US is reviewed herein. Significant techniques that permitted monopulse tracking radars to achieve accurate tracking with high efficiency are discussed, including sum-and-difference antenna feed networks, multi-horn and multi-mode feeds, precision mechanical pedestals, and space-fed arrays. The discussion concentrates on surface-based radars, but many of the techniques apply to airborne radars and missile seekers developed during the same periods.

FIRST-GENERATION MONOPULSE RADARS, 1940-1955

The evolution of monopulse radar in the US from its inception in 1940 to systems deployed today is shown in Figure 1. The earliest work appears to have been done at the Naval Research Laboratory (NRL) in 1940. Parallel efforts at the General Electric Company (GE) during the early 1940s were followed by developments at the Radio Corporation of America (RCA) and the Sperry Gyroscope Company.

Note: This was presented at the Space Research Institute, USSR Academy of Sciences, Moscow, 12 November 1991, during a visit sponsored by the Aerospace and Electronic Systems Society. It is offered herein as a contribution to radar history. The 1991 exchange with Russian radar engineers led to the preparation and publication in the ***IEEE AES Magazine****, May 1998, of the "History of Monopulse Radar in the USSR," by Alexander I. Leonov, a leading Russian expert, developer, and author on monopulse radar.*

Author's Current Address:
80 Lyme Road, Apt. 1004, Hanover, NH 03755, USA.

Review of this manuscript was handled by Ilia Progri. Manuscript received July 10, 2009.
0885/8985/10/ $26.00 USA © 2010 IEEE

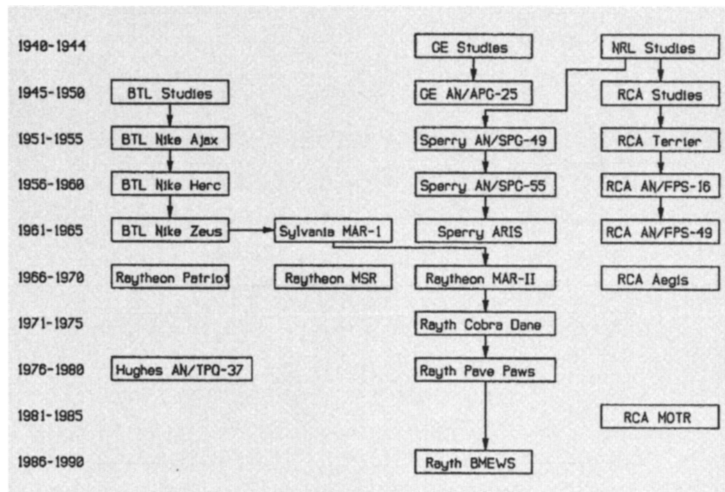

Fig. 1. Evolution of monopulse radars, 1940-1990

The Bell Telephone Laboratories (BTL) became involved by 1945, under the Nike surface-to-air missile program. These organizations remained the principal centers of monopulse radar work into the late 1960s. NRL continued to support the field with theoretical studies, but was not directly responsible for radar development. GE did little work in tracking radar after about 1960. Sperry continued to support naval tracking radar, but had less success in new programs. BTL took themselves out of the military radar business in 1970, and has played no role since that time.

Naval Research Laboratory

Monopulse radar was first discussed in reports at NRL, one of which has been published in open literature [1]. In this report, R.M. Page mentions the previous use, in radio direction finding, of systems in

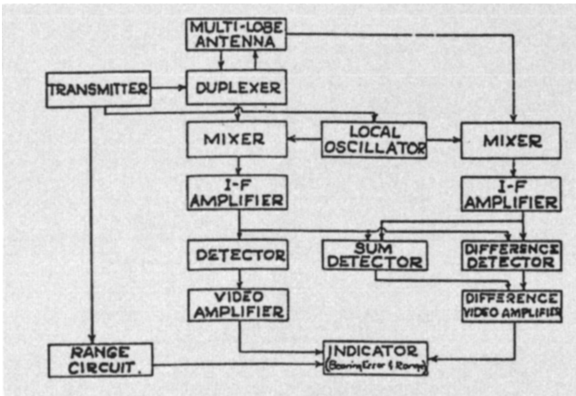

Fig. 2. Block diagram of NRL modified null system [1]

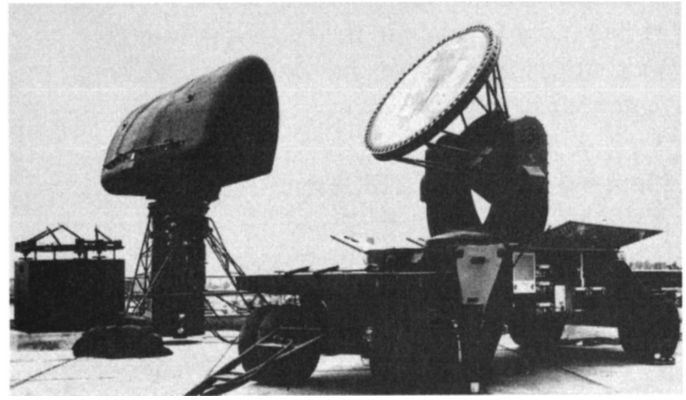

Fig. 3. Nike Ajax search and monopulse target tracking radars (*Bell Laboratory photograph*)

which simultaneous comparison of signal energy in two lobes was applied to eliminate the error caused by signal fading. However, a new idea expressed in the NRL report was the provision of a central lobe for transmission and reception of a ranging signal, with four surrounding lobes providing different signals for azimuth and elevation sensing. This was not the four-horn feed later used for generation of sum-and-difference patterns, but rather was to be a five-horn feed, similar to that eventually used by RCA in the AN/FPS-49 BMEWS search-track radar. The basic block diagram of the proposed NRL system is shown in Figure 2. While some work has been done on monopulse radar at NRL as early as 1940, no operational equipment using this principle was produced during World War II.

Bell Telephone Laboratories: Nike Ajax

One of the earliest postwar developments in monopulse radar was carried out at BTL: the Nike Ajax command-guided surface-to-air missile system (Figure 3). Monopulse tracking was selected as the only technique which could provide the accuracy required for command guidance to maximum missile range. The study leading to this radar development was carried out in 1946, and the first test model was built in 1949 [2, p. 373]. The term monopulse was first proposed for this technique by H.T. Budenbom of BTL in 1946, and has since been accepted in preference to *simultaneous lobing* or the British term *static split,* even when CW signals rather than pulses are used.

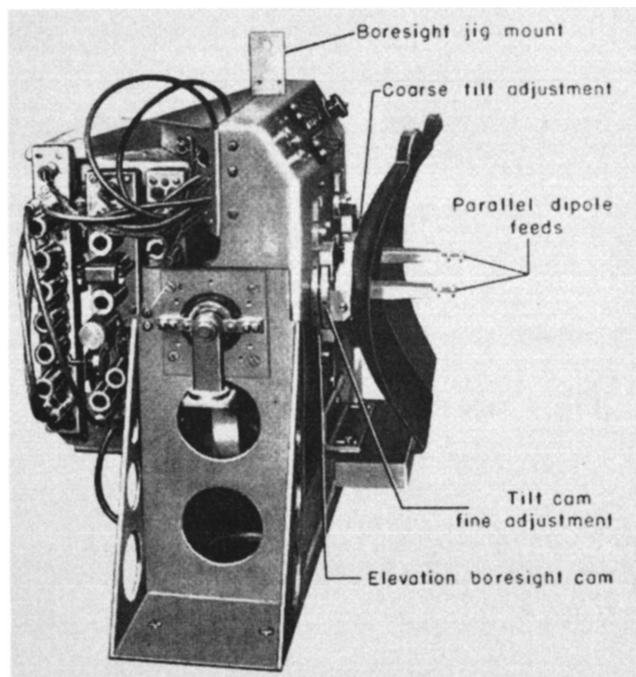

Fig. 4. AN/APG-25 tail-turret fire control radar [4]

In the Nike system two trackers were required; one tracking the incoming target, and a second tracking and guiding the interceptor. Since the two radars were on separate trailers, problems of alignment were critical, as well as quality of tracking by

individual radars. A discussion of performance issues of this radar is given in the section entitled Monopulse Feed Horns for Reflector and Lens Antennas herein.

General Electric Company: AN/APG-25 and AN/TPQ-5

The contributions of GE appeared primarily in the form of a classic study of monopulse theory by G.M. Kirkpatrick [3]. This report laid the theoretical basis for calculating potential precision of monopulse tracking, for comparing different antenna techniques,

Fig. 5. AN/SPG-49 Talos tracking radars (*US Navy photograph*)

and for many other supporting techniques which have since appeared in practical equipment. Among these are:

- the use of the electrical error signal to correct output data for servo lags,
- use of doppler filtering in sum-and-difference channels to extend tracking range in noise and avoid clutter errors, generation of sum (S) and difference (D) illumination by excitation of high-order modes within the feed horn,

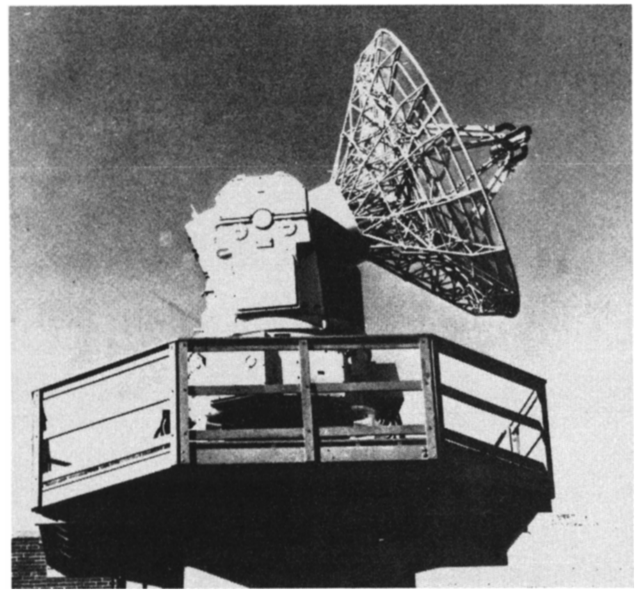

Fig. 6. AN/FPS-16 instrumentation radar (*RCA photograph*)

- normalization of the error signal by limiting and phase detection of S + jD signals, use of RF or IF commutation to cancel detector bias errors, and
- use of off-axis tracking to improve low-elevation performance over reflective surfaces.

One application of the GE work was the AN/APG-25 fire control radar for aircraft tail turrets (Figure 4). This is one of the few radars to use the phase-amplitude monopulse system, invented by W. Hausz of GE [4]. Less successful was the GE development of a counter-battery radar, designated the AN/TPQ-5. This was one of a series of fruitless developments in the counter-battery field, in which attempts were made to replace the conical-scanning systems based on the World War II SCR-584. It was not until the success of the Firefinder phased array systems in the 1970s that significant progress was made in this area of tracking radar. The theoretical issues of amplitude and phase monopulse, not

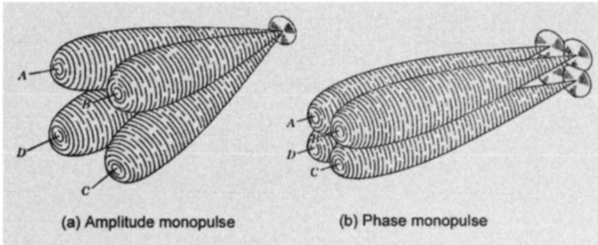

Fig. 7. Simple view of monopulse antenna beams [5]

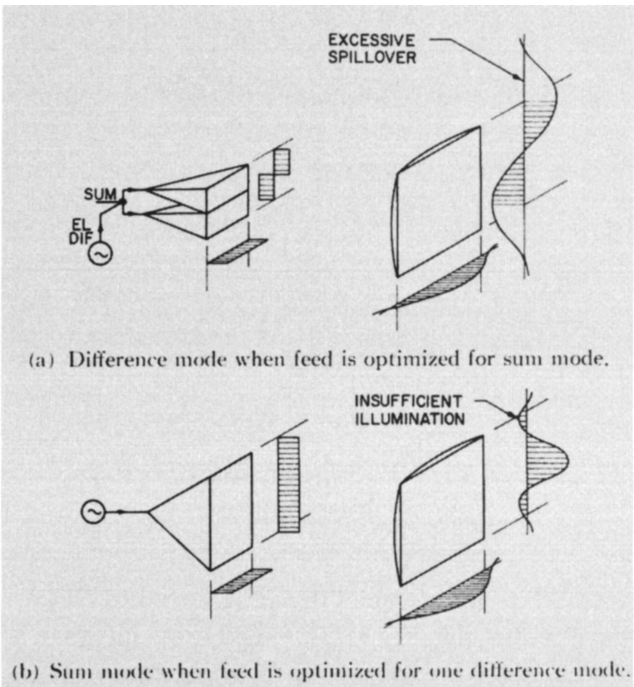

Fig. 8. Four-horn feed illumination limitations [8]

previously covered in professional literature, were explored in the early text by Rhodes [5], based on his doctoral dissertation.

Sperry Gyroscope Company: AN/SPG-49

Sperry was active during the late 1940s and through the 1950s in the development of naval fire control radar. Their initial entry into monopulse radar was the AN/SPG-49, a large C-band monopulse tracker using a metallic lens antenna (Figure 5). This radar supported the Talos missile system. The three-axis pedestal and shipboard installation precluded obtaining high accuracy, but the homing-guidance missile did not require such accuracy.

Radio Corporation of America: Bumblebee Program, AN/FPS-16 and AN/FPQ-4

The first RCA efforts in tracking radar were carried out under the Bumblebee Program, a Navy-sponsored development of surface-to-air missile technology dating to the late 1940s, under the direction of the John Hopkins University Applied Physics Laboratory. Little has been published on these efforts. In 1953, however, the RCA work led to their receiving an Army contract for the development of a land-based version of the Terrier missile system. When the land-based Terrier program was cancelled in 1954, the tracking radar developed for this system became the basis for the AN/FPS-16 precision instrumentation radar (Figure 6).

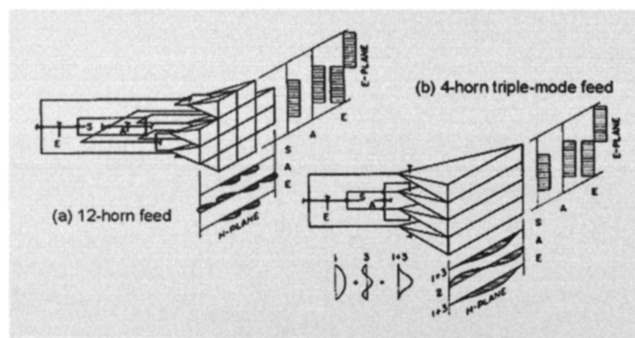

Fig. 9. Multi-horn and multi-mode monopulse feeds [8]

The requirements for the AN/FPS-16 instrumentation radar were developed in 1952 by Ozro M. Covington and this author, working in the Signal Corps detachment at the White Sands Proving Ground. A series of modifications to the conical-scanning SCR-584 had been developed to adapt that radar to range instrumentation functions, but it was clear that accuracy requirements of the test range could only be met by a modern monopulse radar designed especially for instrumentation. The management of the White Sands range failed to

support the idea of precision radar, so the requirements were carried to the Army Signal Corps Laboratories at Ft. Monmouth, New Jersey by this author in 1953, where a study was undertaken to establish detailed technical specifications for the new radar development. In 1954, the development contract for a C-band instrumentation radar was awarded to RCA, based largely on their having

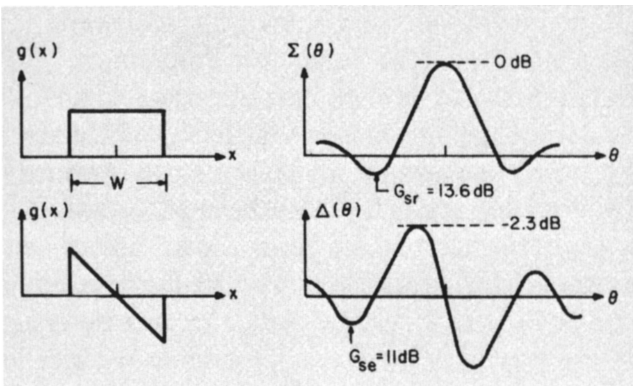

Fig. 10. Ideal monopulse illumination functions for noise environment

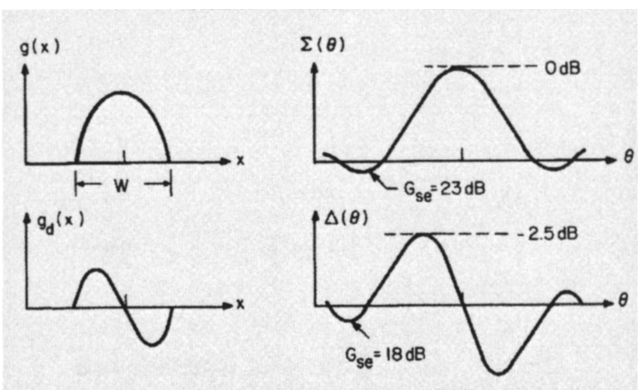

Fig. 11. Practical monopulse illuminations for real environment

successfully demonstrated a very precise pedestal and monopulse receiver for the X-band Terrier radar.

The radar development under Army control was terminated early in the contract, on the basis of an unfavorable evaluation of project feasibility by a Technical Panel on Electronics, appointed by the Defense Department and consisting of executives

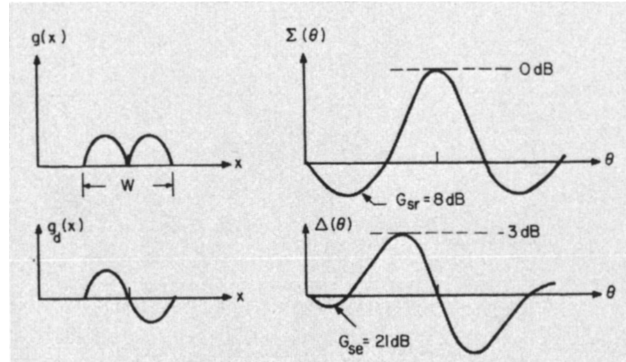

Fig. 12. Phase monopulse illuminations for a dual-reflector antenna

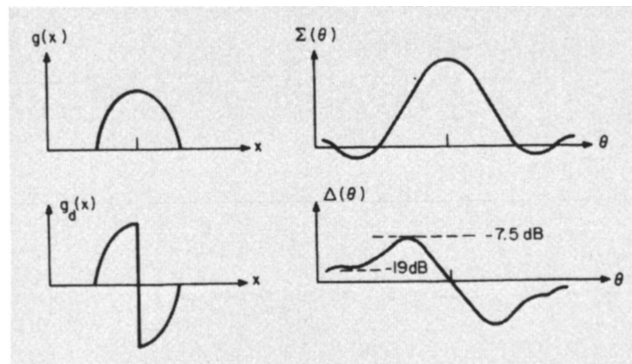

Fig. 13. Phase monopulse illuminations for a phased array

from BTL, Sperry, and GE. Transferred to Navy sponsorship, the AN/FPS-16 development was continued to become one of the most successful radar programs in post-war history. Additionally, since the radar was designed for instrumentation rather than as part of a weapon system, it was possible for this author to describe its design and performance in the professional literature [6, 7], as well as in contract reports. In 1957, after a successful flight test program, a production contract for twenty-five radars was issued to equip the major US missile test ranges. White Sands Proving Ground, although still dominated by engineers committed to optical and CW doppler instrumentation technology, received eight of the new radar systems. These have since become the basic instruments for trajectory measurement at White Sands and at test ranges worldwide.

MONOPULSE FEED HORNS FOR REFLECTOR AND LENS ANTENNAS

Apart from precision mechanical pedestal technology, the key to design of accurate monopulse tracking radars was the technology of monopulse feed horns. Early workers considered the antenna in terms of multiple, but independent, horns (amplitude monopulse) or separate apertures (phase monopulse), which could be combined into sum-and-difference channels to achieve boresight stability. This concept led to several difficulties in deployed radar systems, to be discussed below. Ultimately, it has become necessary to view the monopulse antenna in terms of its aperture illumination functions, and to design the feed system to produce an approximation of the desired functions.

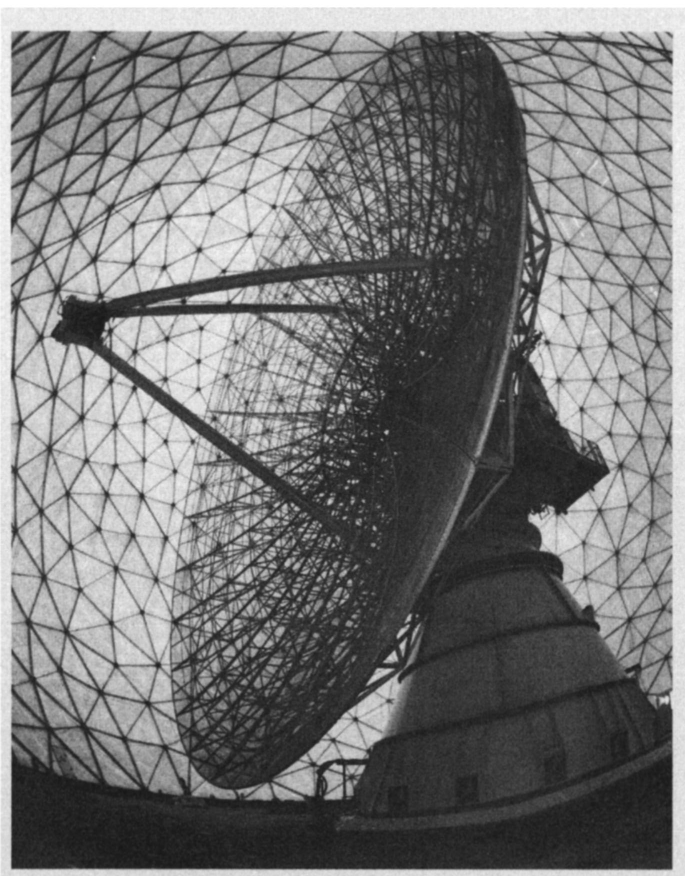

Fig. 14. AN/FPS-49 BMEWS search-track radar (*US Air Force photograph*)

Amplitude-Comparison Monopulse

The conventional view of the amplitude monopulse antenna (Figure 7A) considers four squinted beams, formed by a cluster of four horns at the focal point of a reflector or lens. The relative amplitudes of signals received in these four beams provide the angle sensing information. When processed by a sum-and-difference (Σ and Δ) system, microwave networks form the Σ channel as the in-phase sum of these four beams. The Δ channels for azimuth and elevation are formed in these same networks by placing pairs of horns in anti-phase.

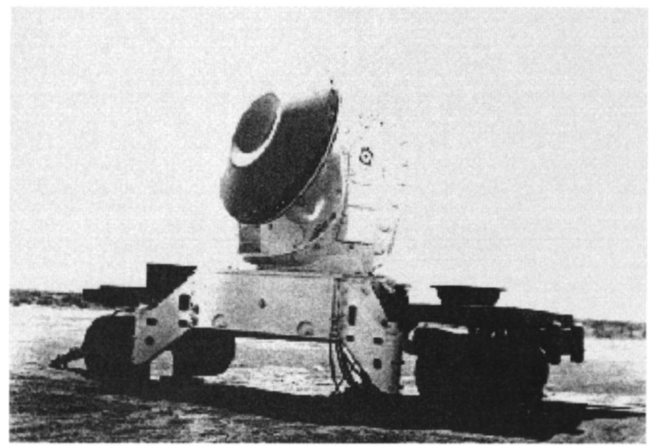

Fig. 15. Nike Hercules tracking radar (*Bell Laboratory photograph*)

Phase-Comparison Monopulse

Phase monopulse is conventionally considered in terms of four parallel beams (Figure 7B) formed from four aperture quadrants displaced around a central axis. The relative phases of signals received in these four beams provide the angle sensing information. Sum-and-difference processing may be applied to this system, using microwave networks as in the case of amplitude monopulse.

Sum-and-Difference Illumination Functions

When the Nike Ajax test model was operated at White Sands Proving Ground, unexpectedly large errors appeared in the elevation data. After thorough mechanical testing exonerated the pedestal and data output devices, we discovered that large antenna sidelobes, responding to ground-reflected (multi-path) signals, were the source of error. The

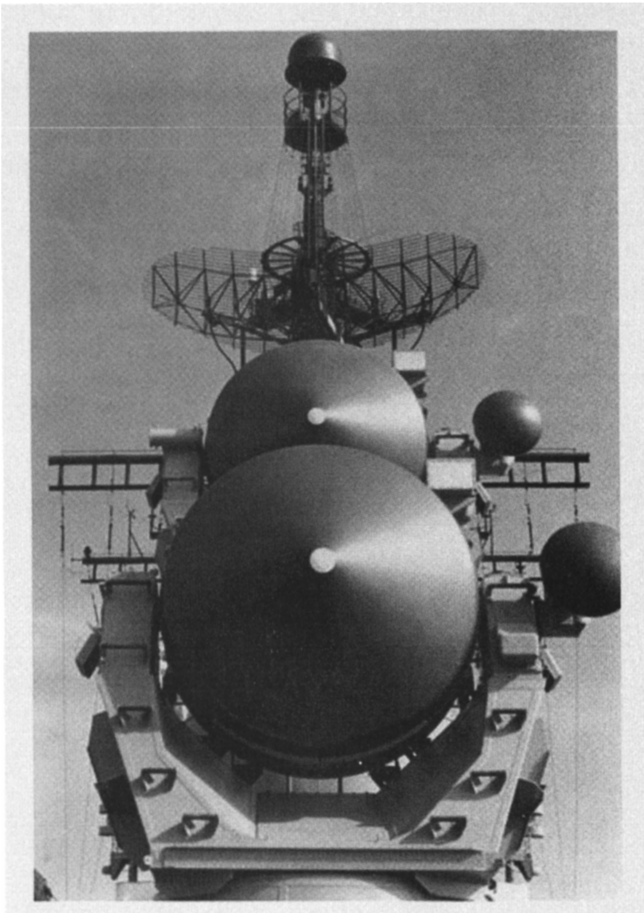

Fig. 16. Sperry's AN/SPG-55 tracking radar (*Sperry Gyroscope photograph*)

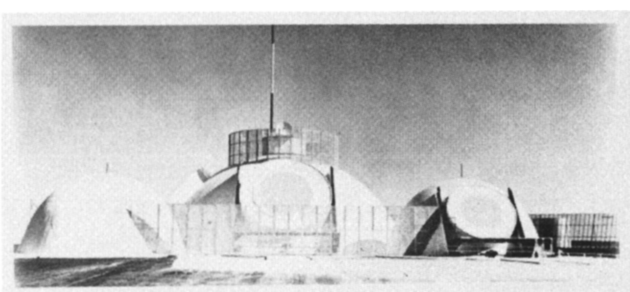

Fig. 17. Sylvania MAR-I at WSMR [2]

metallic lens was one source of these sidelobes, but the basic four-horn feed design was the major contributor. A study was commissioned by BTL and carried out by Peter Hannan at Wheeler Laboratories [8], which described the problem and its solution.

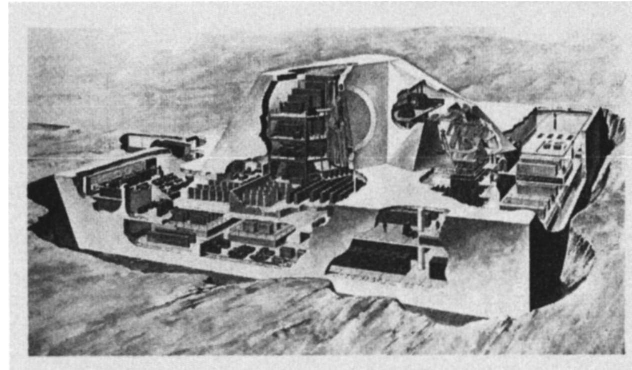

Fig. 18. Raytheon MAR-II concept [2]

The basic four-horn monopulse feed cannot simultaneously produce illuminations for efficient, low-sidelobe Σ and Δ patterns. If the total width of the horn cluster is adjusted for good Σ illumination, the Δ illumination will have high edge intensity and spillover (Figure 8A). If the total width is optimized for good Δ illumination, the Σ illumination will be concentrated in the center of the aperture (Figure 8B), giving low efficiency.

Multi-horn and Multi-mode Feeds

Hannan found the solution to the monopulse feed problem in the multi-horn and multi-mode feeds designs of Figure 9. Through the use of additional couplers, the Δ channels use additional horns at the periphery of the feed, confining illumination to the aperture while retaining also an efficient Σ illumination. A multi-mode feed was also evolved at RCA for the AN/FPS-16, providing reasonable sidelobe levels and efficiency although not fully exploiting the design features of the Hannan feed.

Monopulse Illumination Functions and Patterns

When considering the performance of different monopulse implementations, it is useful to return to Kirkpatrick's derivation of the optimum Σ and Δ illumination functions for the thermal noise environment (Figure 10). The uniform Σ illumination gives maximum gain, while the linear-odd Δ illumination gives maximum measurement slope. However, the high sidelobe levels make these *"ideal"* functions unsuitable for use in the real radar environment.

Application of taper to both Σ and Δ illuminations produces practical functions, as shown in Figure 11. Both gain and measurement slope are decreased, but sidelobe levels are greatly reduced. In constrained-feed phased arrays, the Σ illumination is often chosen from the Taylor family of low-sidelobe tapers, while the Δ illumination may be a Bayliss taper. Approximations to the illuminations shown in Figure 11 may be generated with the feed horn clusters shown in Figure 9, as well as by array-constrained feed networks. Whether these illuminations are called *"amplitude monopulse"* or *"phase monopulse"* in systems using Σ - Δ processing is an arbitrary choice: the two sides of the aperture will have Δ illuminations of opposite phase, while the Σ illumination will have uniform phase across the aperture.

When the illumination functions of the conventional phase monopulse antenna approaches are compared, the results will appear as in Figures 12 and 13. In Figure 12, each of two side-by-side reflectors is illuminated with a cosine function, and the two outputs are added and subtracted in a hybrid junction. The resulting Δ pattern is good, but the Σ pattern has low-gain and high-sidelobes. In Figure 13, a phased-array aperture is illuminated with a cosine function, and a hybrid junction in the center produces the odd Δ illumination function. In this case, the Δ pattern has unacceptable sidelobes. Neither of these types of antenna provide adequate performance in the real radar environment.

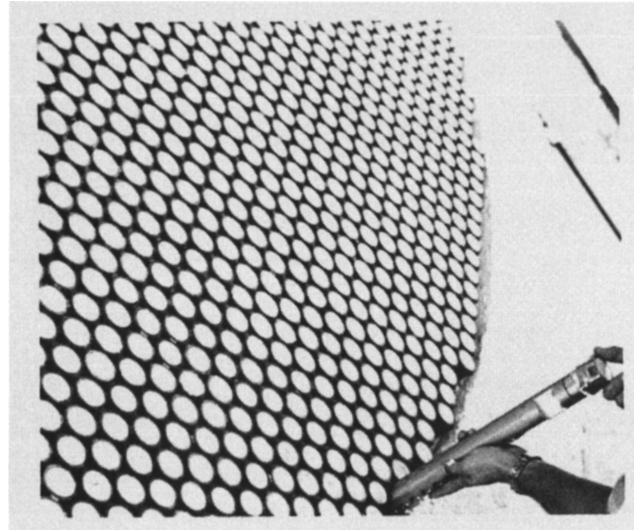

Fig. 19. MSR array element installation [10]

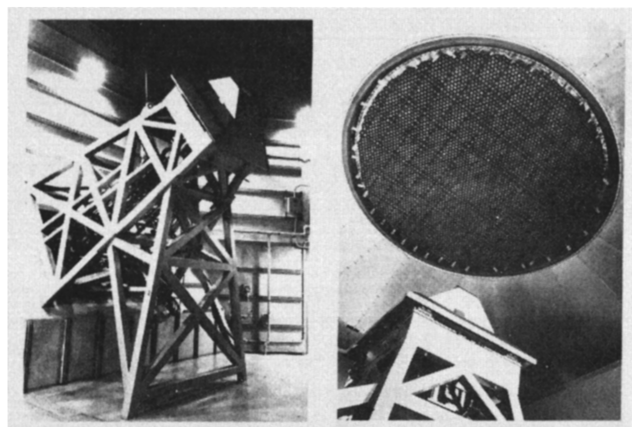

Fig. 20. MSR feed-horn and antenna chamber [10]

MONOPULSE RADAR DEVELOPMENTS, 1955-1965

The second generation of monopulse tracking radars using mechanical pedestals and reflector antennas with advanced feeds became available during the late 1950s and early 1960s. These were produced primarily by the four organizations already mentioned as having developed the early systems.

RCA:
AN/FPQ-4, AN/FPS-49, Tradex

Immediately after starting AN/FPS-16 development, RCA received a contract for a land-based version of the Talos missile system. The AN/FPQ-4, developed to support this missile system, was almost identical to the AN/FPS-16, using the same pedestal, antenna, receiver system, and servos. A high-power klystron transmitter was included, based on the original AN/FPS-16 design.

In 1957, requirements for a long-range ICBM-detection radar were formulated by the US Air Force. RCA developed a 425 MHz triode transmitter with 300 kW average power, intended by the Air Force to be used with a huge toroidal parabolic antenna (later to become the AN/FPS-50 radar). However, by scaling the AN/FPS-16 parameters to the longer wavelength,

Fig. 21. Patriot multi-function phased array (*Raytheon Company photograph*)

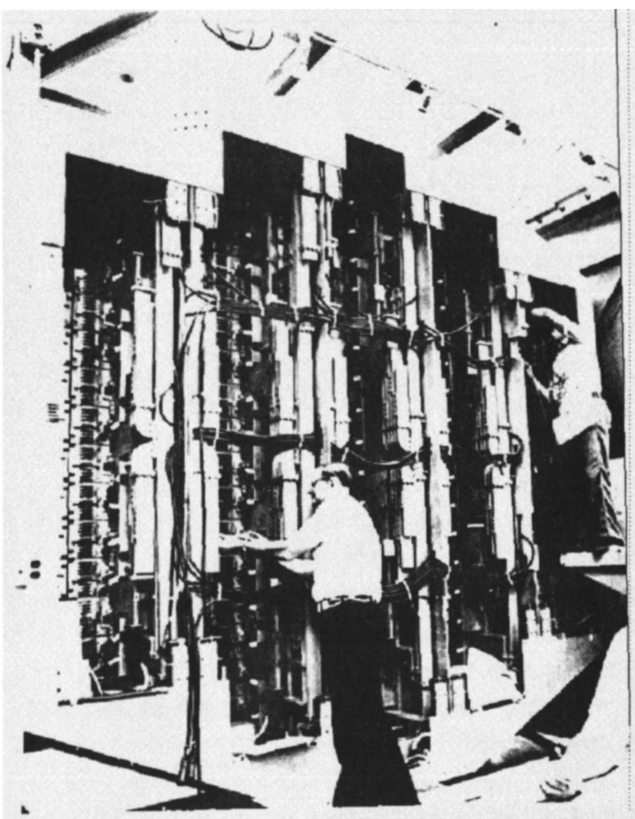

Fig. 22. Aegis array viewed from the rear (*RCA photograph*)

it was found by RCA that a radar having 4000 km detection range on 1-m^2 targets could be built as a monopulse tracker. The radar would search a narrow elevation sector just above the horizon, locking onto and tracking any target which penetrated this search fence. Positive discrimination of ballistic missiles from satellites and other false alarms could be obtained during the tracking. The necessary 52 dB scaling from the AN/FPS-16 produced the AN/FPS-49 (Figure 14), with a 25 m antenna diameter and five-horn feed (anticipated by Page in his 1944 report).

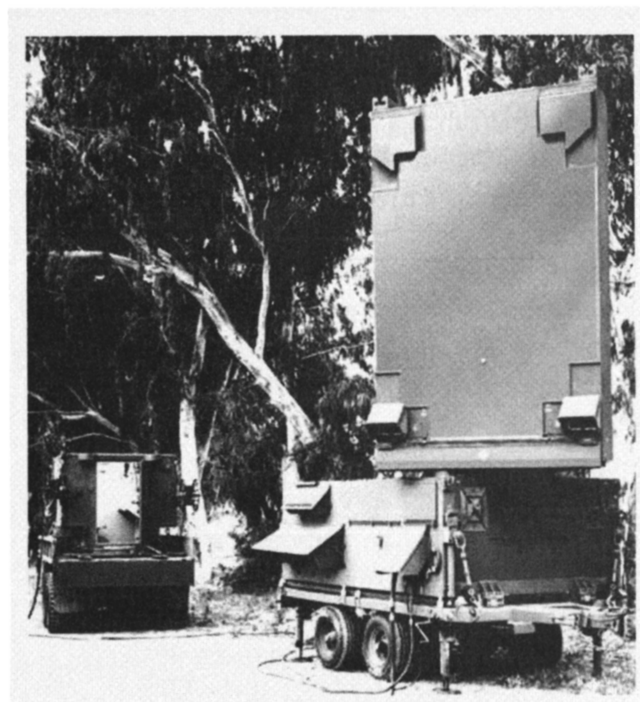

Fig. 23. AN/TPQ-37 counter-battery radar (Hughes Aircraft Company photograph)

The central Σhorn provided circular polarizations to overcome the effects of Faraday rotation in the ionosphere. AN/FPS-49 radars were ultimately installed along with the AN/FPS-50s at the Clear, Alaska site and, in preference to the AN/FPS-50, at the British BMEWS site.

The Tradex radar was an adaptation of the AN/FPS-49, used for instrumentation at the Kwajalein Atoll in the Pacific [9]. This paper describing Tradex is the only example in the professional literature of a monopulse tracking radar using pulsed Doppler processing.

Bell Telephone Laboratories: Nike Hercules and Nike Zeus

The Army requirement for longer missile range, along with the limited accuracy of the Nike Ajax radar at low elevation angles, led to development of the Nike Hercules system. The missile range was extended to 90 km, and radar tracking accuracy improvements were able to support this range with acceptable miss distance.

The Hannan multi-mode feed design was used in the Nike Hercules tracking radar (Figure 15) with great success. Accuracy of this system approaches that of the AN/FPS-16 instrumentation radar. In addition to optimizing the feed, Wheeler Laboratories designed the polarization-twist Cassegrain reflector system to replace the original lens. Mechanical design features used in the AN/FPS-16 pedestal were also included. This type of reflector system has been used in many subsequent radars, providing low blockage and excellent mechanical characteristics.

Development work was also done at BTL during the late 1950s on radars for ABM systems. The Nike Zeus Target Tracking Radar (TTR) used a 6 m reflector antenna at C-band, achieving 1000 km tracking range against targets of 0.1 m^2. Many techniques developed for Hercules were applied to this radar.

General Electric Company: Atlas Guidance Radar

One of the successful applications of GE monopulse radar technology was in the guidance radar for the Atlas ICBM. Combining radar and inertial data, the guidance system was able to meet high accuracy requirements for long-range ballistic missiles. However, this mode of guidance was rapidly replaced by pure inertial guidance systems, requiring minimal ground support and having no vulnerability to ECM.

Sperry Gyroscope Company: AN/SPG-55

The second generation of monopulse radar designed at Sperry was the AN/SPG-55, supporting the Navy's Terrier surface-to-air missile. Two of these radars are shown in Figure 16.

MONOPULSE PHASED ARRAY RADAR, 1965-1991

Radar development efforts in the US since 1965 have been primarily directed toward phased array systems. Successful as was the BTL Nike Hercules development, it turned out that the firepower of this command-guidance system fell far below what was desired. Radars having multiple-target capability were deemed essential. Defense against aircraft, tactical ballistics missiles (TBMs) and long-range ballistic missiles were included as requirements in a new generation of systems.

Sylvania Electronic Systems: MAR-I

As part of the BTL Nike-X system, a contract was let to Sylvania in 1961, leading to development, installation, and testing during 1961-1965 at White Sands Missile Range of the Multi-function Array Radar, Model I (MAR-I). This phased array system is shown in Figure 17. This multi-function radar was intended to provide search, discrimination, and precision tracking of targets. Separate arrays were used for transmitting and receiving. There is disagreement as to the degree of success achieved in this development, but subsequent development of MAR-II was assigned by BTL to the Raytheon Company.

Raytheon Company: MAR-II, MSR, Patriot

Raytheon was not a major participant in monopulse radar development during the 1950s, concentrating instead on coherent Doppler systems. Many engineers believed that the requirements for monopulse receivers were inconsistent with those for pulsed-Doppler operation. However in the class of large multi-function arrays used in ABM applications, Raytheon established an important design capability which led to the award of the MAR-II contract. This radar was developed and installed on Kwajalein Atoll (Figure 18). It featured high peak and average power (100 MW and 3 MW, respectively), separate transmit and receive arrays, formation of multiple simultaneous beams, and elaborate signal processing functions. Work on a common-aperture version of this radar (CAMAR) led

to the successful Raytheon development of radars such as Cobra Dane, Pave Paws, and, more recently, the phased-array replacements for the BMEWS radars. All of these are monopulse systems using transmit-receive modules, the latter two implemented with solid-state transmitting sources.

Another Raytheon development for the BTL ABM systems was the Missile Site Radar (MSR). This was a shorter-range system to control the intercept of re-entry vehicles. After thorough study, BTL accepted the Raytheon recommendation for use of a space-fed array, in preference to a corporate (constrained) feed. The phase-shifting lens (Figure 19) was illuminated by a high-power monopulse feed of the Hannan design (Figure 20). Two MSRs were built; one at the Kwajalein Atoll, and one near Grand Forks, North Dakota.

During this same period, Raytheon was engaged in competition with RCA and Hughes Aircraft for the Army Field Army Ballistic Missile Defense System (FABMDS, later to become SAM-D and then the Patriot). The multi-function radar concept owed much (both in advantages and limitations) to the previous studies of ballistic missile defense. Emphasis was placed on high-energy, single-pulse waveforms for most search and tracking actions. The limited time budget allows for MTI waveforms in both search and track in beam positions where clutter reduction is needed. Illumination for the semi-active (target-via-missile, or TVM) seeker took the form of pulsed doppler bursts, but these were not used in the radar itself. The space-fed lens array (Figure 21) consists of some 5000 non-reciprocal ferrite phase shifters, which must be switched on each pulse between transmitting and receiving.

A major advantage of the space-fed array is its ability to exploit the excellent multimode feed designs originated by Hannan for the Nike systems. The Σ and Δ illumination functions produced by this horn system were near optimum for efficiency, measurement slope and low sidelobes. Spillover has been minimized and it was considered unnecessary to place any special absorber around the antenna system.

RCA:
Aegis

Soon after award of the SAM-D contract, another competition was sponsored by the US Navy for Advanced Shipboard Missile System (ASMS), later to become Aegis. This was won by RCA (subsequently incorporated into GE, and then Lockheed Martin), with a constrained-feed sub-array concept. Each sub-array is fed from its own power amplifier, permitting very high peak and average powers to be radiated without problems of waveguide breakdown. However, the segmentation of the array presents difficulties in achieving low sidelobes. The monopulse network consists of a 40:3 microwave beamformer, coupling each of the 40 sub-arrays to all three monopulse channels (Figure 22). Attempts to convince the Navy that a space feed would be advantageous have not been successful. RCA/GE also developed a Multiple Object Tracking Radar (MOTR) for test range instrumentation using a space-fed lens array.

Hughes Aircraft Company:
Firefinder AN/TPQ-37

Hughes Aircraft, while unsuccessful in major competitions for ABM and SAM radar equipment, developed many successful airborne radars using monopulse processing, and into the ground-based field has developed and placed in production two types of counter-battery radar. The AN/TPQ-37 (Figure 23) is an artillery location radar designed for about 30 km range. Diode phase shifters provide scanning over a 90° sector in azimuth and over a more limited elevation sector. Monopulse tracking is used to refine target trajectories. A smaller AN/TPQ-36 radar uses array technology that is unable to implement monopulse.

CONCLUSIONS

This has described the state of monopulse radar art in the US through the year 1991 with emphasis on surface-based systems. Most of the organizations in which the development were carried out have evolved since that time, and this author has not attempted to update these organizational changes, or to discuss the recent evolution in monopulse radar. We believed, however, that the background given herein will be useful for those who wish to develop a clearer understanding of the background in this important area of radar technology.

REFERENCES

[1] R.M. Page,*
Accurate Angle Tracking by Radar,
US Naval Research Laboratory Report RA 3A 222A,
28 December 1944.

[2] M.D. Fagin, Ed.,
A History of Engineering and Science in the Bell System: National Service in War and Peace,
Bell Telephone Laboratories, 1978.

[3] G.M. Kirkpatrick, *
Final Engineering Report on Angular Accuracy Improvement,
Contract DA 36-039-sc-194, 1 August 1952;
originally classified, downgraded to unclassified.

[4] W. Hausz and R.A. Zachary, *
Phase-amplitude monopulse system,
IRE Trans. on Military Electronics,
MIL-6, No. 2, April 1962, pp. 140-146.

[5] D.R. Rhodes,
Introduction to Monopulse,
New York: McGraw-Hill, 1959;
reprinted, Artech House, 1980.

[6] D.K. Barton, *
Accuracy of a monopulse radar,
IRE 1959 Military Electronics Conference Proc.,
1959, pp. 179-186.

[7] D.K. Barton,
Radar System Analysis,
Englewood Cliffs, NJ: Prentice-Hall, 1964;
Dedham, MA: Artech House, 1976.

[8] P.W. Hannan, *
Optimum feeds for all three modes of a monopulse antenna,
IRE Trans. Antennas and Propagation, **AP-9**, No. 5,
September 1961, pp. 330-351.

[9] J.T. Nessmith, *
New performance records for instrumentation radar,
Space/Aeronautics, December 1962, pp. 86-93.

[10] Bell Telephone Laboratories,
ABM Research and Development at Bell Laboratories: Project History,
Contract DAHC60-71-C-0005, October 1975.

---

* These papers were reprinted in *Radars, Vol. 1, Monopulse Radar,* (D.K. Barton, ed.), Dedham, MA: Artech House, 1974.